Chapter 2

APPLICATION OF SIGNAL PROCESSING METHODS IN ISLANDING AND POWER QUALITY DISTURBANCE DETECTION

2.1 INTRODUCTION

The increasing complexity of the electric grid requires intensive and comprehensive signal monitoring followed by the necessary signal processing for characterizing, identifying, diagnosing, and protecting and also for a more accurate investigation of the nature of certain phenomena and events. Signal processing (SP) can also be used for predicting and anticipating system behavior [90]. In this chapter, a basic overview of SP has been given.

2.2 SIGNAL PROCESSING METHODS

For electrical engineering, SP is a vital tool for clarifying, separating, decomposing, and revealing different aspects and dimensions of the complex physical reality of electrical systems [91]. Different phenomena are usually intricately and intrinsically aggregated and not trivially resolved.

- SP can be qualified by the electrical systems' analytical aspects and can help expose and characterize the diversity, unity, meaning, and intrinsic purpose of electrical parameters, system phenomena, and events.

- As the electric grid becomes more complex, modeling and simulation become less capable of capturing the influence of the multitude of independent and intertwined components within the network. SP deals with the actual system and not with modeling abstraction or reduction (although it may be used in connection with simulations), so it may clarify aspects of the whole through a multiplicity of analytical tools. Consequently, SP allows the engineer to detect and measure the behavior and true nature of the electric grid. Figure 2.1 shows the SP methods used for the application of islanding and power quality disturbance detection.

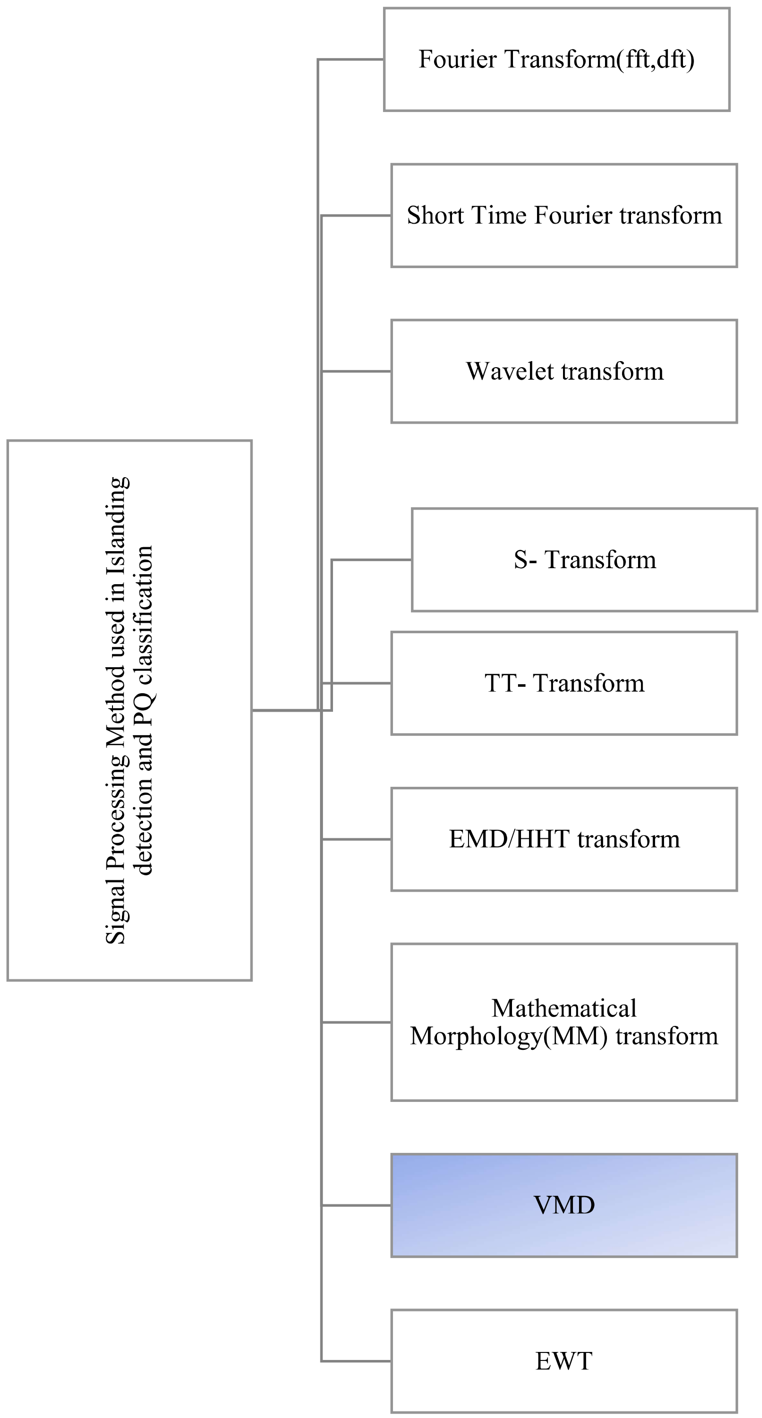

Figure 2.1 Signal Processing Methods

2.2.1 Fourier Transform

FT is a popular technique used for frequency-domain analysis, wherein a signal is characterized by a series of sinusoidal signals of different frequencies [9]. It simply decomposes the factual time-domain signal into complex exponential functions at various frequencies level. It helps analyze the different frequency content of the factual signal as the coefficients of the decomposed signal represent the contribution of every frequency level. The FT of time-domain signal $f(t)$ is given by:

$$F(\omega) = \int_{-\infty}^{\infty} f(t).e^{-j\omega t}dt \qquad 2.1$$

t is time; $F(\omega)$represents the signal in the frequency domain. However, FT cannot resolve any transient information associated with dynamic variations. Therefore, to overcome this problem, time-frequency analysis is proposed.

2.2.2 Short-Time Fourier Transform

Short-Time FT (STFT), a modification of FT, segregates a signal into small frames, wherein each frame can be treated as stationary. A moving window technique is further applied to evaluate all these frames, which allows us to have a time-frequency analysis of the signal. The STFT of a signal F(t) is given by:

$$STFT\{F(t)\} \equiv X(\tau,\omega) = \int_{-\infty}^{\infty} F(t).W(t-\tau)e^{-j\omega t}dt \qquad 2.2$$

$W\ (t)$ is used window function, maybe a rectangular, Gaussian, or Hamming window. It has been observed that even though STFT gives better representation than FT, but one significant particularity of STFT is that the sliding window length is constant throughout the whole plane. The disadvantage, however, is that STFT cannot be applied to non-stationary signals due to the fixed window width. However, by selecting an appropriately small window, STFT can be used to identify transients in voltage disturbance signals.

2.2.3 Wavelet Transform

For outperforming the limitations of FT (no time information) and of STFT (fixed frequency and time localization), another signal processing tool called WT has been introduced by Grossman and Morlet in 1984. Wavelets are mathematical functions and are associated with building a model for a non-stationary signal with a set of components that are small waves. The difference lies in the fact that, in wavelet analysis, the signal is characterized by small waves, called wavelets, generated from a fixed function called the mother wavelet. These wavelets are localized in both time and frequency, thus making WT a suitable candidate for time-frequency analysis of signals because wavelets have short windows at high frequencies, and large windows at low frequencies can depict the dynamic behavior transients discontinuities. The WT can effectually represent the factual signal with a minimal number of coefficients as it has a specific localization attribute of the wavelets. A mathematical function can be called a mother wavelet if it meets the following two conditions:

$$i)\ \int_{-\infty}^{\infty} \psi(t)dt = 0 \qquad 2.3$$

$$ii)\ \int_{-\infty}^{\infty} |\psi(t)|^2 dt < \infty \qquad 2.4$$

The WT has been categorized mainly into two types as follows:

i) Continuous wavelet transform (CWT)

ii) Discrete wavelet transform (DWT)

2.2.4 Empirical Mode Decomposition

The Empirical Mode Decomposition mechanism is an adaptive signal decomposing algorithm. Its versatility and effectuality make it apt for extracting the prime features of the non-stationary signals. Compared with the above-mentioned classical signal processing mechanisms like FT, STFT, or wavelet algorithms, it has a considerable adaptation. Furthermore, EMD is free from selecting any preset mother mathematical function like the wavelet transformation. It comprehensively outperforms the major concern of wavelet transform, i.e., picking the proper mother wavelet and level of decomposition. It has been significantly utilized to analyze the nonlinear and nonstationary signals by decomposing the factual signal into different mono component functions termed intrinsic mode functions (IMFs) by applying a shifting mechanism. The obtained IMFs contain vital information about the factual signal. The concept of IMFs was firstly introduced in the year 1998 by Huang et al. There are two mandatory criteria for being the decomposed function to be IMFs are as follows:

i) The extreme and number of zero-crossing should be the same, or at most differ by one.

ii) At any point, the mean of upper and lower envelopes defined by the local extremal is zero.

According to the sifting mechanism initially, the lower and upper envelopes of the factual signal are figured out by determining the local extrema of the original signal. The envelopes are constructed simply by using the smooth interpolation technique. Thereafter, the mean of the acquired envelopes is termed the local mean of the factual signal. It can be set as the reference which separates the lower and highest frequency oscillations in the original signal. By subtracting the estimated local mean from the factual signal, we obtain the first set of IMFs (if it satisfies the mandatory criteria). Afterward, the residue has been computed, and the same sifting mechanism is repeated for acquiring the subsequent IMF and a new residue till the residue value is more than the threshold value.

The steps of EMD are given below:

- Identify the local minima (M) and maxima (m) of input signal $V(t)$
- Execute interpolation between M and m for acquiring envelopes $e(t)_{min}$and $e(t)_{max}$
- Compute the average of the envelopes using

$$m(t) = \frac{\left[e_{max}(t) + e_{min}(t)\right]}{2}$$

- Extract $C_1(t) = V(t) - m(t)$
- $C_1(t)$is an IMF if it meets the criteria as mentioned earlier. If $C_1(t)$is not an IMF, then repeat steps 1to 4 on$C_1(t)$, so long as new acquired $C_1(t)$ meets the criteria.
- Compute the residue, $r_1(t) = V(t) - C_1(t)$
- If the $r_1(t)$ is more than a threshold value, then repeat steps for acquiring the next IMF and a new residue.

2.3 RECENT SIGNAL PROCESSING METHODS

S-Transform (ST) consolidates the properties of STFT and WT, and it is based on a moving and scalable Gaussian window. ST constructs a time-frequency representation of a time-series signal and offers frequency-dependent resolution and simultaneous localization of imaginary and real spectra. It also gives multi-resolution while keeping the phase of respective frequency components unaffected, which comes in handy for disturbance detection in a noisy environment. TT transformation (TT-T) is a ST technique that presents one-dimensional (1D) time-series data in a 2D TT-series representation. TT-transform aids in providing an enhanced time localization of a signal through scaled windows. Morphological filters are basically non-linear signal transformation tools. Two fundamental morphological operators in MM are dilation and erosion. Dilation is an expanding process, whereas erosion is a shrinking transform.

More robust versions have since been proposed to address the sensitivity of the original EMD algorithm concerning noise and sampling. Empirical Wavelet Transform (EWT) explicitly builds an adaptive wavelet basis to decompose a given signal into adaptive subbands. This model relies on robust preprocessing for peak detection, then performs spectrum segmentation based on detected maxima and constructs a corresponding wavelet filter bank. The filter bank includes some mollification (spectral overlap) flexibility, but explicit frequency bands still appear slightly strict.

2.4 VARIATIONAL MODE DECOMPOSITION

The generalized comparison of the SP method has been given in Table 2-1 and in terms of time-frequency decomposition in Table 2-2. The current decomposition models are mostly limited by 1) their algorithmic ad-hoc nature lacking mathematical theory (EMD), 2) the recursive sifting in most methods, which does not allow for backward error correction, 3) the inability to properly cope with noise, 4) the hard band-limits of wavelet approaches, and 5) the requirement of predefining filter bank boundaries in EWT.

To overcome mentioned above limitation, a variational model that determines the relevant bands adaptively and estimates the corresponding modes concurrently, thus properly balancing errors between them. Motivated by the narrow-band properties corresponding to the current common IMF definition and an ensemble of modes that reconstruct the given input signal optimally (either exactly or in a least-squares sense), while each being band-limited about a center frequency estimated online has been proposed by D. Zosso in 2014 [92]. A detailed discussion about VMD has been presented in the next chapter.

Table 2-1 General comparison of Signal Processing Method

	Fourier	**Wavelet**	**EMD**	**EWT**	**VMD**
Basis	a priori	a priori	adaptive	adaptive	adaptive
Frequency	convolution: global, uncertainty	convolution: regional, uncertainty	differentiation: local, certainty		
Presentation	energy-frequency	energy-time-frequency	energy-time-frequency		
Nonlinear	no	no	yes	yes	yes
Non-stationary	no	yes	yes	yes	yes
Feature extraction	no	discrete: no, continuous: yes	yes	yes	yes
Theoretical base	theory complete	theory complete	empirical	Theory complete	Theory complete

Table 2-2 Comparison in Time frequency decomposition technique

Method	Bandwidth	Data Adaptive	Separate closely spaced frequencies
Wavelet	Fixed	no	no
EMD	variable	yes	no
EWT	variable	yes	yes
VMD	variable	yes	yes

2.5 SUMMARY

In this chapter, the concepts of recent signal-processing methods and characteristics have been thoroughly described. In the coming chapters, VMD concepts have been utilized for realizing the islanding detection and power quality disturbance detection problem.